# A 14,000 year-old-record from a coastal freshwater lake: Sedimentological evidence for tsunamigenic events on the west coast of Vancouver Island, British Columbia, Canada

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**Abstract.** During the Holocene, numerous great earthquakes have occurred along the west coast of North America. Enormous seismic waves, triggered by these colossal forces of nature, have episodically inundated vulnerable regions of the Cascadia coastal lands to elevations of up to 20 m above mean sea level. The destructive paths of tsunamis leave behind important geological evidence like anomalous sheets of gravel and sand containing marine fossils and terrestrial detritus marking a distinct disturbance in the depositional environment. Such tsunamigenic deposits can be found in low-elevation lakes; depositional environments which allow one to determine the distribution and inland range of the tsunami wave run-up but also ideal environments because they tend to preserve a longer and older sedimentological record.

Multiple inferred tsunami deposits were recorded in Kakawis Lake, on the west central coast of Vancouver Island, and have provided a 14,000-year-old record of information. The tsunamigenic sediments predate AD 1700 and are similar to those found in other lakes on the Island. As for a regional correlation, these tsunami deposits are likely related to at least two and possibly three of the events reported in the Atwater and Hemphill-Haley chronology, with recurrence intervals of about 400 years.

## 1. Introduction

Anomalous sandy layers attributed to allochtonous processes have been recognized in many different coastal environments along the Pacific coast of the North American continent. These texturally coarse-grained layers, interpreted to be deposited by the action of tsunamis, are considered important and interesting geological evidence of historical and pre-historical tectonic activity along the Cascadia Subduction Zone (CSZ) (Fig. 1a). The CSZ has the lowest interplate seismicity of any other convergent margin around the Pacific Ocean, but it is one of the largest tectonically active systems in North America (Heaton, 1990; Yeats *et al.*, 1997; Clague, 1996). Nevertheless, Cascadia has produced devastating mega-thrust earthquakes ($M > 8$) episodically in the geologic history of this region, with recurrence intervals ranging from 300 to 500 years.

On Vancouver Island, numerous sites with tsunamigenic deposits (Fig. 2) have been identified along some of the west coast's fjords, mainly in tidal marshes, beaches, and sub-bottoms of bays (Clague *et al.*, 1992, 1994; Clague and Bobrowsky, 1994a, 1994b, 1999). The identification and analysis of

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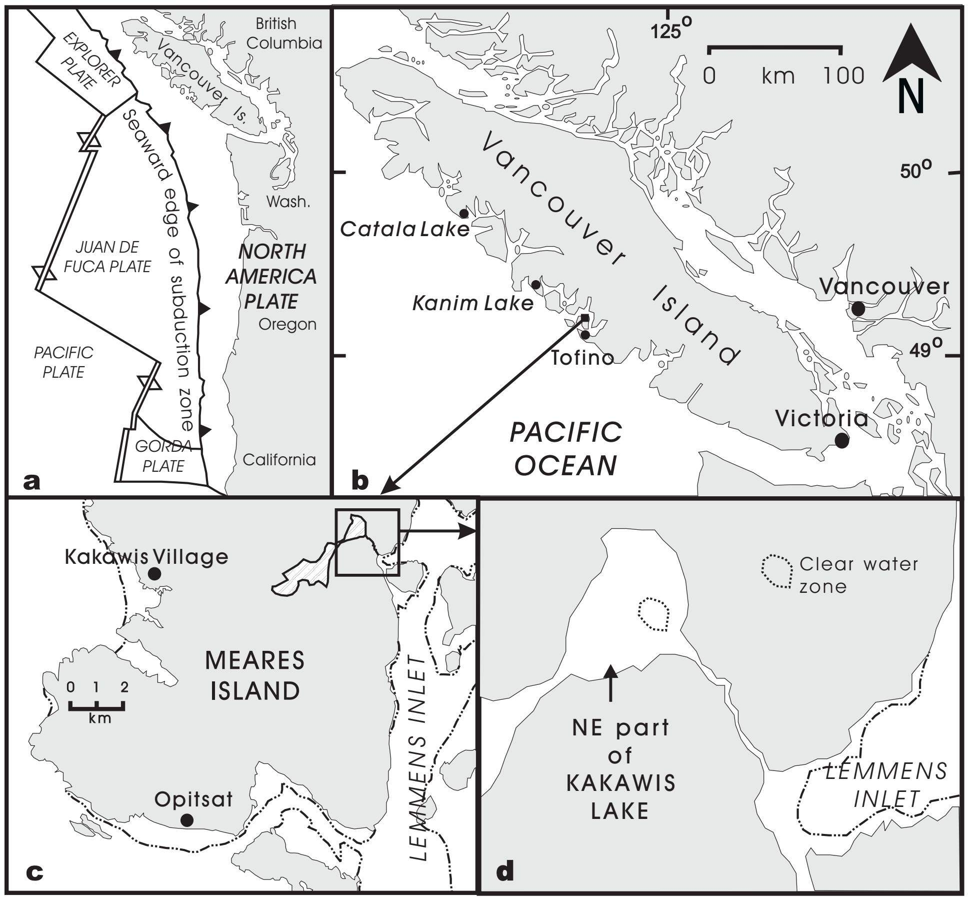


**Figure 1**: The study area. (a) Tectonic setting of the Cascadia Subduction Zone. (b) Vancouver Island, British Columbia, showing the location of the study site, important lakes, and places mentioned in the text. (c) The environs of Kakawis Lake. Dashed lines represent the outermost limits of tidal flats at low tide. (d) Close-up of the NE lobule of Kakawis Lake body, focus of the study. The central area of this lobule is not covered by aquatic vegetation.

tsunamigenic deposits provide insight into their characteristics, including the recurrence interval of repetitive catastrophic events on the Island.

## 2. Overview of the Research

Low-elevation lakes (<5 m above mean sea level –asl–) situated close to seashore have been a more recent target in the study of palaeo-tsunami deposits (Bobrowsky *et al.*, 1999; Clague *et al.*, 1999; Hutchinson *et al.*, 1997, 2000). These coastal freshwater lakes (Fig. 2), located in an area above the influence of tides or storm surges, offer an ideal environment to study the impact of tsunamis and to estimate the minimum wave run-up reached (Fig. 3). Such environments do not present the problems encountered with marshes, beaches, or bays regarding preservation of the tsunami deposits. Such problems include: continuous littoral processes, erosion, low sedimentation rates,

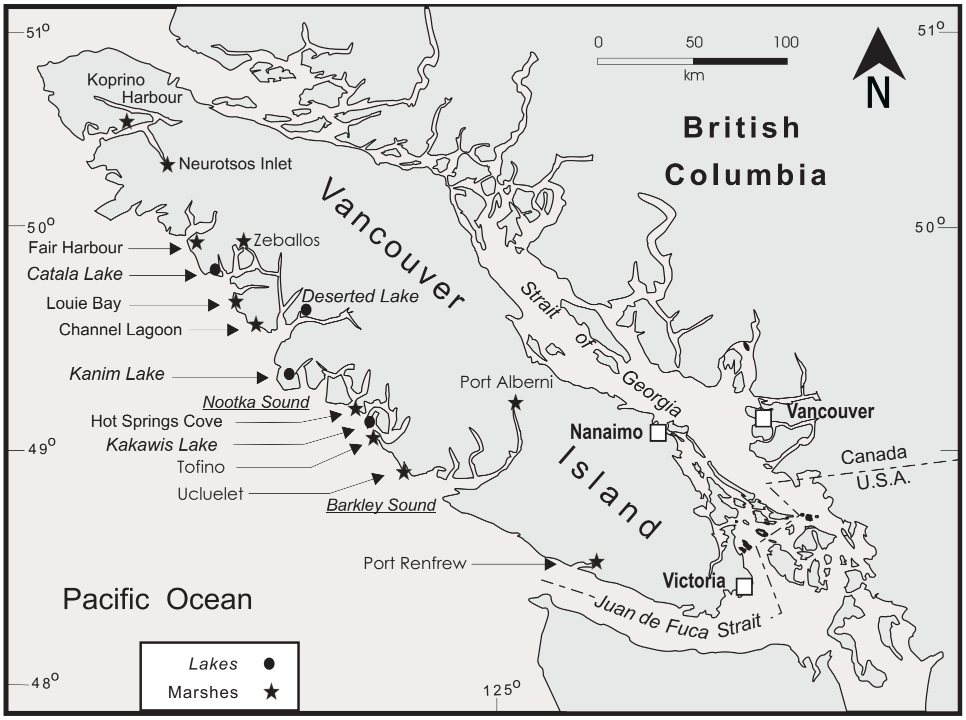


**Figure 2**: Location of sites presenting geological evidence of tsunami deposits in marshes and lakes on the west coast of Vancouver Island, British Columbia.

regional uplift and subsequent vegetation invasion and bioturbation. The estimated "life-time" of a marshal area in the region is considered to be no more than ~1000 years, after which all evidence of past tsunamigenic sands could be lost (Clague *et al.*, 1982; Friele and Hutchinson, 1993; Clague, 1996). It is important to note that the probability of finding tsunami deposits in lacustrine environments is proportional to the topography of the submarine floor near the coastline, the shape of the bay, inlet, or channel through which the wave travels (Pelinovsky *et al.*, 1998), and the availability of material on the path. A protected, semi-secluded, but active lacustrine system is even more responsive to high-magnitude external changes because the normal pattern of sedimentation would be rapid and noticeably affected.

## 3. Description of the Study Area

Kakawis Lake is found approximately 4.5 km north of Tofino in west-central Vancouver Island, British Columbia, lying within the limits of the West Vancouver Island Fjordland and Estevan Lowlands's physiographic regions of Vancouver Island (Yorath and Nasmith, 1995). It is located in the western peninsula of Meares Island (Figs. 1b, c, d), which is bordered by steep-sided rocky slopes of volcanic and metamorphic bedrock, with shallow tidal marshes developing only where outlet streams flow or small bays open. Kakawis Lake has an elevation of approximately 3–4 m asl and is

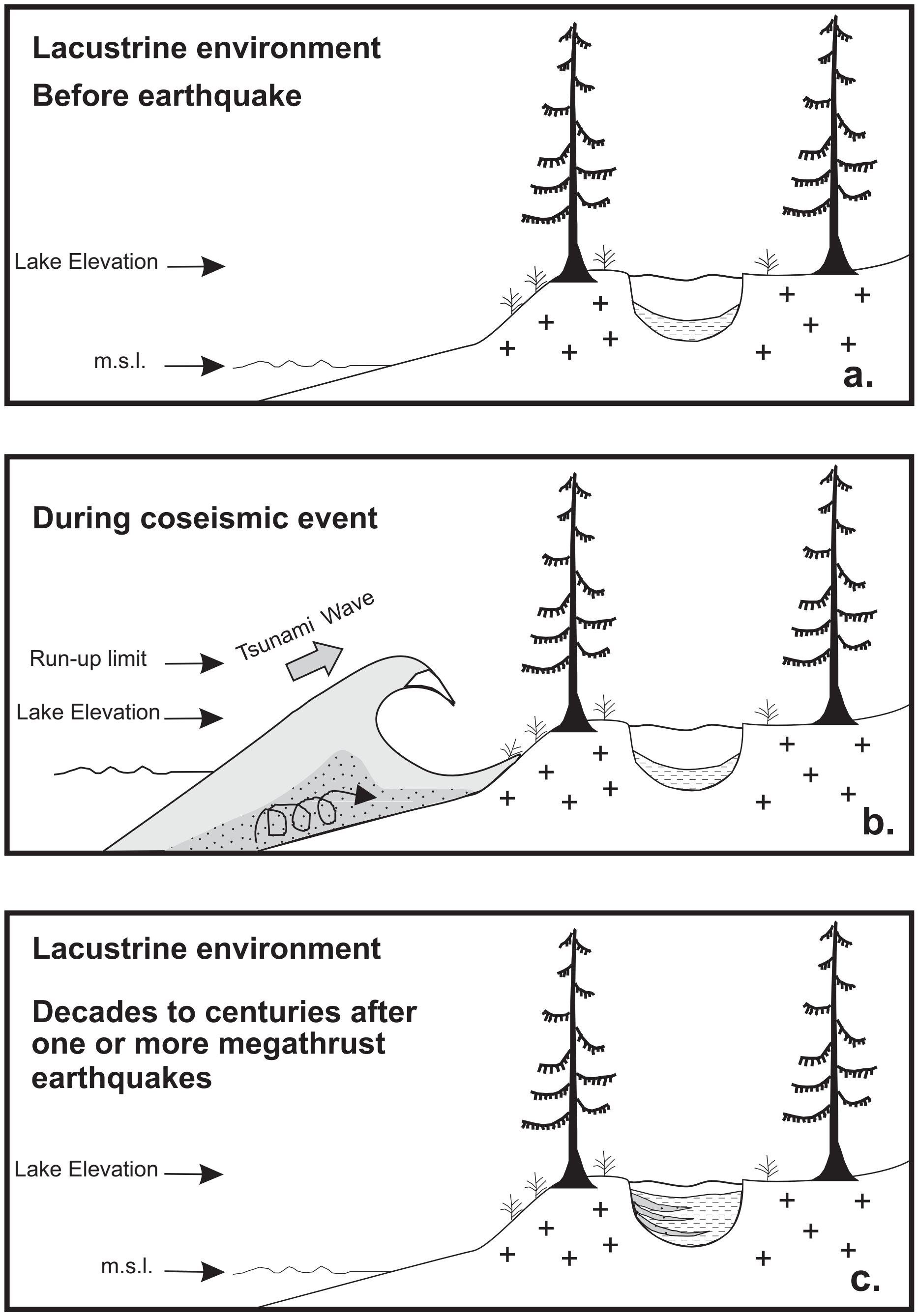


**Figure 3**: Diagram showing the possible origin of coastal geological evidence for Cascadian megathrust earthquakes in low elevation lakes: the coseismic deposition of tsunami sands. (a) The general setting of lacustrine environment close to seashore before an earthquake. (b) The same environment during the earthquake, showing triggered tsunami wave. (c) The environment after any earthquake.

surrounded by a dense coniferous temperate rain forest (highly confined). No steep slopes are present in the immediate margins of the lake. Partially restricted to the direct action of open-ocean waters, Lemmens Inlet is the only aquatic pathway that can direct a seismic wave into this lake. Furthermore, it has a short (500 m long and <10 m wide) outlet stream that can easily act as a channel to incoming run-up.

## 4. Methods

A modified version of the percussion coring system of Reasoner (1993) was utilized. Six substantial cores were obtained from Kakawis Lake, of which three exceeded depths of 5 m below lake bottom. The cored area was the right part (200 m in diameter and 3 m deep) of the major Kakawis Lake body, which has the direct outlet stream to saline waters. The cores were taken mainly from the central part of the lake, facing the entrance to the outlet stream (Fig. 1c, d). Detailed lithological descriptions, photographing, physical properties and textural analyses, and sub-sampling were done in the laboratory. Several samples of plant detritus (wood, bark fragments, twigs, needles, and cones) and fragments of shells selected along the cores were dated by accelerator mass spectrometry (AMS) at Isotrace Laboratory (University of Toronto). Since terrestrial plant detritus can often be reworked and thus redeposited within the lacustrine sediments, the youngest age obtained would then better represent a minimum age for the enclosing sediment. The radiocarbon ages obtained in this research are also cited as calibrated age ranges, determined from the standard data set INTCAL98 found in Stuiver *et al.* (1998).

## 5. Stratigraphy of the Lacustrine Sediments of Kakawis Lake

Tsunami deposits typically thin and fine landward and contain brackish and marine microfossils (Atwater, 1992; Darienzo *et al.*, 1994; Clague, 1996; Bobrowsky *et al.*, 1999). Plant detritus of diverse sizes and reworked submarine shelf or intertidal material can be encountered within the sand sheet and/or toward its top. At Kakawis Lake, at least one and probably up to four sandy deposits were found in the stratigraphic record of the cores, indicating that past landward surges of seawater washed into the lake at several times during the Holocene. The composite stratigraphy of Kakawis Lake based on the correlation of distinctive units and radiocarbon dates is presented in Fig. 4.

The lowermost unit consists of a light bluish-grey clay containing fragments of marine bivalves, has been interpreted to be of glaciomarine origin. The clay is overlain by a dark brown to black organic mud unit with a very sharp, but undulating lower contact. Both units are only present in the deepest part of one core (Kakawis #5). Common to all cores is a major unit containing the tsunami horizons, consisting of a laminated to horizontally bedded olive grey organic mud with minor amounts of shell fragments and abundant plant detritus. Laminations increase toward the top of this unit

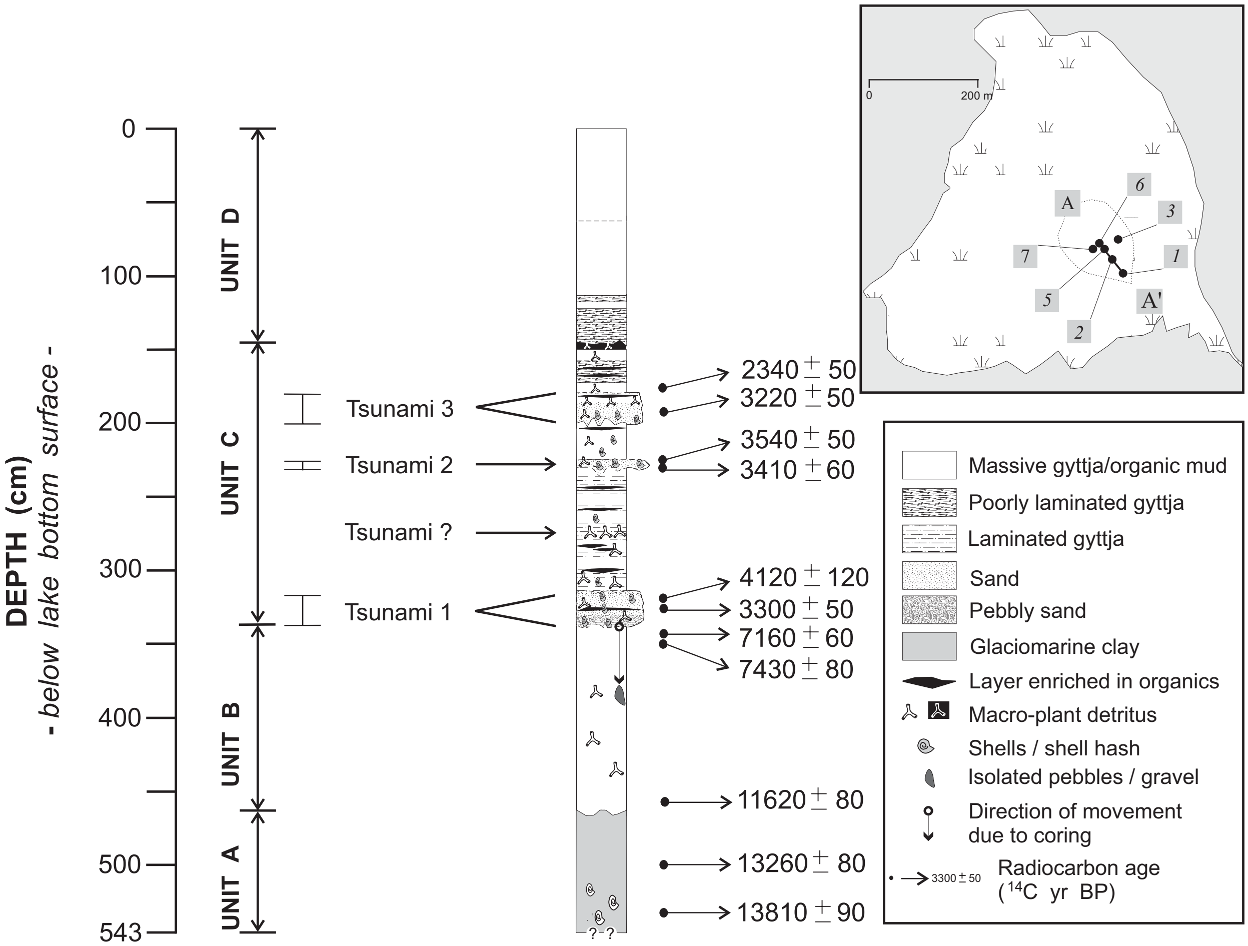


**Figure 4**: General lithostratigraphy of the sub-bottom of Kakawis Lake. Indications of depth (below lake bottom surface) are given, as well as the different main units described in the text. Specific emplacements of tsunami layers are shown and the positions where some of the samples were taken for radiocarbon dating. Top right box: A close-up of the NE lobule of Kakawis Lake shows the location of the six cores taken along an A–A′ transect facing the outlet stream. The only area of the lake that is not covered by aquatic vegetation is shown in the center of the water body.

and may be result of seasonal or annual sediment budget variations in the depositional environment.

All the tsunamigenic horizons have a similar structure: massive, chaotic deposits with loose grains and lower water content as compared to the surrounding mud or gyttja. The lowest (oldest) tsunami layer varies from 16 to 23 cm in thickness, and is texturally bimodal, consisting of a mix of medium to coarse sand and gravel, shell fragments with low amounts of plant detritus, and a silty matrix. The sedimentology suggests that this tsunami layer, recorded in three cores, was deposited by a succession of at least three wave surges, due to the closely spaced intercalation between much smaller 5-cm sheets. The lower contact in this unit is erosional. Radiocarbon analyses on twig fragments collected below the lower contact give an age range of 7160±60 $^{14}$C years BP (5985–6030 years BC) and 7430±80 years BP (6220–

6395 years BC). Other twig and wood samples collected within this layer give an age range between a minimum of $3300 \pm 50$ $^{14}$C yrs BP (1515–1635 years BC) and a maximum of $4120 \pm 120$ $^{14}$C years BP (2550–2880 years BC). In cores Kakawis #6 and #7 there is evidence for another possible tsunamigenic deposit between the lowest and the middle deposits. Further detailed examination is required for a more robust interpretation, as it mainly consists of repeated small-scale laminations of plant detritus with minor concentrations of shell fragments.

The middle tsunami layer is texturally uni-modal, the sand is finer grained, and there is considerably more plant detritus accumulated toward the top of the layer. In core Kakawis #7 a maximum thickness of 20 cm was observed. The age range, obtained from bark and twigs retrieved in this layer, varies between $3410 \pm 60$ $^{14}$C years BP (1680–1750 years BC) and $3540 \pm 50$ $^{14}$C years BP (1805–1940 years BC).

The upper (and most recent) tsunami layer is up to 30 cm in thickness, and is present in all the cores. It is bimodal in texture, with medium sand to pebbles in a silty sand matrix. It is the most chaotic of all the sandy deposits, and the one that appears to represent the most energetic event of all three, due to the size and type of material contained within. A radiocarbon age of $3220 \pm 50$ $^{14}$C years BP (1430–1520 years BC) was obtained from one pine cone found within the deposit. Another date obtained from needles and twigs collected from the upper contact gives an age of $2340 \pm 50$ $^{14}$C years BP (385–409 years BC). This tsunami deposit is overlain by a dark brown to dark olive silt and sand-rich gyttja. It displays weak laminae and a gradational upper contact. Abundant macroscopic plant detritus occurs throughout and shell fragments (also abundant) occur near the bottom of the unit. The uppermost unit of the cores consists of a brown gyttja, interpreted to represent modern freshwater lacustrine sediments.

## 6. Holocene History and Discussion

To date, Kakawis Lake has experienced a minimum of three main tsunami events: the oldest occurring some time between 3515 and 3975 calendric (cal) years BP, the second between 3680 and 3750 cal years BP and the most recent between 2385 and 2409 cal years BP. The events may have occurred closely in time. Interestingly, tsunami deposits related to the 1964 Alaska earthquake, the AD 1700 Cascadia earthquake, and a tsunami from an unknown source between 500 and 800 years ago reported in the marshes near Tofino (Clague and Bobrowsky, 1994a, 1994b, 1999; Clague, 1996) are not present in the stratigraphic record of Kakawis Lake.

The tsunamigenic deposits in Kakawis Lake predate AD 1700, suggesting that only tsunamis older than 1000 years ago are present in lakes on the west coast of Vancouver Island (Clague, 1996). Similar early deposits have been found in Kanim, Catala, and Deserted Lakes (Table 1) on Vancouver Island (Hutchinson *et al.*, 1997, 2000; Clague *et al.*, 1999). For the entire Cascadia region, the most recent and best estimate of average recurrence intervals (~500 years) for mega-thrust earthquakes comes from detailed work

**Table 1**: Chronology and correlation between the ages of the Atwater and Hemphill-Haley (1997) identifiers and the tsunami deposits found in different lakes on the west coast of Vancouver Island. (a) Letters correspond to event identifiers for Cascadia subduction zone earthquakes, based on buried soils present in marshes at Willapa Bay (Washington coast, U.S.A.). Ages are given in years BP and calendar year. (b) Identified low elevation lakes on Vancouver Island recording consequent tsunami deposits attributed to different earthquake events. Elevations and depths of each lake as well as lengths of outlet streams are given. Datum for lake elevation is mean sea level. Outlet stream length is the approximate distance of lake from seashore (Sources: Atwater and Hemphill-Haley, 1997; Clague *et al.*, 1999; Hutchinson *et al.*, 1997, 2000—except for Kakawis Lake (current research)).

| **(a) Mega-thrust earthquake chronology**[a] | | | | **(b) Cored lakes on the west coast of Vancouver Island**[b] | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | **Kakawis** | **Kanim** | **Deserted** | **Catala** |
| | | | | **Elevation (m):** | **3–4** | **6** | **3** | **~3** |
| | | **Estimated** | **Calendar** | **Outlet stream (m):** | **300** | **700** | **500** | **500** |
| **Identifier** | **Age BP**[c] | **Range** | **Year** | **Depth (m):** | **3** | **~2** | **20** | **1** |
| Alaska | 36 | 36 | AD 1964 | | | | | |
| Y | 300 | 300–300 | AD 1700 | | | | × | × |
| Alaska? | 800 | 800? | AD 1200? | | | | | |
| W | 1100 | 1000–1300 | AD 1000–700 | | | | ×? | × |
| U | 1300 | 1200–1300 | AD 900–700 | | | | | |
| S | 1600 | 1300–1700 | AD 700–300 | | | | × | |
| N | 2600 | 2400–2800 | BC 400–800 | | × | × | × | |
| L | 3000 | 2800–3200 | BC 800–1200 | | ×? | | | |
| J | 3400 | 3400–3500 | BC 1400–1500 | | × or older | | | |

[a] Ages of earthquakes at Cascadia and nearby subduction zones.
[b] "×" indicates presence of tsunamigenic deposits according to age shown in (a).
[c] Cal (before AD 2000).

in buried soils in estuaries of SW Washington (Atwater and Hemphill-Haley, 1997). The events recorded in Kakawis Lake are likely related to at least two and probably three of the above mentioned event identifiers (Table 1): the oldest tsunami deposit could represent the J event (3400 cal years BP); stratigraphicaly the middle one to event L (3000 cal years BP) and the latest one could have been produced by the N event (2600 cal years BP). Although the age range analyzed for the main three events recorded in Kakawis Lake is closely spaced in time, they could correspond to the earliest and oldest three events in Atwater and Hemphill-Haley chronology, matching with mean recurrence intervals of 400 years for that period of time. It is also possible that two of the defined events in the lake correspond to several consecutive run-ups of single tsunami surges due to the closeness between tsunamigenic laminae. The tsunamigenic deposits encountered in Kakawis Lake represent the oldest ones found so far on Vancouver Island, British Columbia.

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